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Flash X-Ray : A Diagnostic Tool for Shaped Charge Studies

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ABSTRACT

At present many antitank weapon systems are employing shaped charge warheads. It is, therefore, extremely important for a designer to avail of the methods capable of predicting performance of shaped charges, mainly to achieve maximum penetration. For this purpose, it is necessary to study the behaviour of the shaped charge during actual firing tests. These tests are difficult because of high speed of events that take place, production of intense light, smoke, debris, etc, and the large scale destruction caused. To overcome these difficulties, flash x-ray is being preferably used. The paper gives the details pertaining to the deployment of a 450 kV flash x-ray system during the jet studies on 30, 60 and 90 mm shaped charges and the evaluation of jet characteristic parameters.

NOMENCLATURE

P expected penetration

L total unbroken jet length

ξ_j density of the jet material (copper)

ξ_t density of the target (steel)

1. INTRODUCTION

A shaped charge generally consists of the high performance high explosive charge which usually has a conical cavity at the end facing the target. This shaped cavity or hollow space inspired the name of 'shaped or hollow charge'[1]. This cavity is usually lined with an auxillary symmetric layer of material, such as copper, having a thickness optimised by the designer and the charge which uses a type of technology termed as 'lined shaped charge'. The axial initiation is essential for high penetration performance and is being achieved by a suitable booster charge. The initiation elements, the high explosive charge, the liner, etc. are all held together in a suitable casing which also provides the confinement.

The technology of the shaped charges has advanced in recent years and is being deployed against explosively reactive armours (ERAs) and complex laminated armours[2]. It is generally accepted that a 'good' shaped charge meets tight symmetry tolerances and utilises high quality explosives and liner material. The design parameters of a shaped charge includes : type of explosive, liner material and thickness, cone shape, and cone angle. But, an absolute correlation between specific parameters and performances is required to be established. The main difficulty is encountered in obtaining the data on detonation, jet formation, jet penetration[3], etc. The main jet characteristics are: unbroken jet length, jet tip velocity and break-up time, and the desirable penetration. The penetration rate and the jet velocity data allows to correlate the penetration performance, which depends upon the unbroken length of a fully stretched jet. Various studies show that the liner material manufacturing process and the finish also have major influence on the jet characteristics[4,5], keeping the other variables constant. In addition, particulation of the jet is also one of the important characteristics of a shaped charge. During the jet analysis it is essential to look into the particulation process as this gives an indication of maximum possible penetration. In this process, initially a continuous stretching of the jet takes place due to velocity gradient along its length. As the stretching becomes greater than

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the tensile strength of the material, the jet starts breaking up into particles.

At present, many antitank weapons systems are employing shaped charge warheads, incorporating improvement by way of wave shapers, centering devices, etc. Therefore, it is extremely important for the designer to avail of the methods capable of predicting the performance of shaped charges and assessing the effect of the changes made in the parameters. Consequently, constant efforts are being made all over the world to examine the jet penetration process in depth[6-8]. To ensure the repeatability of the performance, it is necessary to keep the quality check on the production and manufacturing of the copper liners, explosive filling, assembly, etc.

While analysing the performance, the jet break-up time and the total unbroken jet length will indicate the copper quality, with the other design parameters held constant. Held[9] suggested that the essential factor for the greatest possible penetration capacity of a shaped charge is the unbroken jet length determined from the summation of the length of individual particles after the jet break-up. A quality factor of a liner, independent of its calibre, could be obtained by dividing the break-up time by the calibre (or the diameter).

The jet particulation depends upon the methods of production of the liner; the quality of its material, inner and exterior surfaces, and adhesive layer; axisymmetry of the assembly of the various components; the type of explosive charges, etc.

The performance analysis of a shaped charge is a very difficult task as the events are very fast, destructive, and produce intense light, smoke, debris, etc. High speed photography is difficult and complicated requiring special equipment like Kerr cells or the techniques like 'synchrostreak' involving critical alignments, high intensity illumination (like argon flash bombs), semi-silvered mirrors, etc. The electronic methods do not give the required information, such as jet break-up time, jet and jet particle length, velocity of individual jet particles, etc. The flash radiography technique is used as a major diagnostic tool[10-11].

1.1 The Flash Radiographic System

The 450 kV flash radiographic system used for the study, consists of a 50 kV charging power supply, a 450 kV Marx pulse generator[10-14], demountable type x-ray tubes, and a control console containing zero air and freon, high pressure controllers, delay generators, timer/counter modules, ion pump power supplies for holding the vacuum in the x-ray tubes, etc.

It is inconvenient to have very high voltage of the order of 450 kV, mainly due to the insulation requirements. Since a short duration pulse is required to excite the x-ray tube, recourse is taken to the Marx generator. In this case, it consists of a pressure tank having nine 50 kV capacitors, charging resistors and spark-gaps, arranged suitably so that the capacitors can be charged in parallel and discharged in series into the load, the x-ray tube. The discharge in the form of a very high current pulse of a short duration of about 20 ns is thereby obtained. This pressure tank is having two compartments, viz, of 50 and 450 kV. The 50 kV (i.e., low voltage) compartment with the capacitors, spark-gaps, etc is insulated with zero air at different selected pressures depending upon the required voltage of operation. The high side which may have to hold as much as 450 kV is insulated with freon-12 or SF-6 at high pressure. This compartment can hold the x-ray tube directly or can be connected with a limited length of which also carries the freon gas, for remote operation.

For precise synchronisation, the first two spark-gaps are triggered with the trigger pulse at the trigger electrode; and the remaining spark-gaps fire due to over-voltage or self-breakdown.

The experimental details are shown in Fig. 1. The main purpose of the experiment is to observe the jet and to measure the velocity of the jet particles. From the radiographs taken, one can discern the quality of the jet as regards the straightness, shape and size

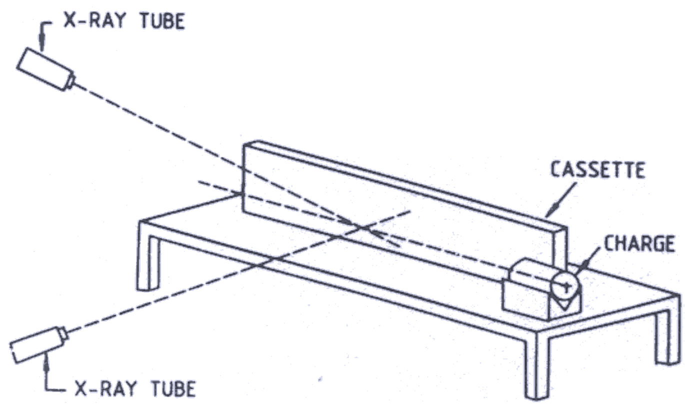

Figure 1. Experimental set-up.

uniformity of the particles, nature of particulation (shear or tensile failure), tumbling/spinning, etc. All these factors affect the penetration.

During the operation, a trigger pulse suitably obtained from the event, is amplified by a pulse transformer/power amplifier and is connected to the initial spark-gaps to cause a voltage breakdown which further triggers the discharge of all capacitors in series into the x-ray tubes. Figure 2 depicts the outline of the system configuration of an x-ray system using the Marx generator.

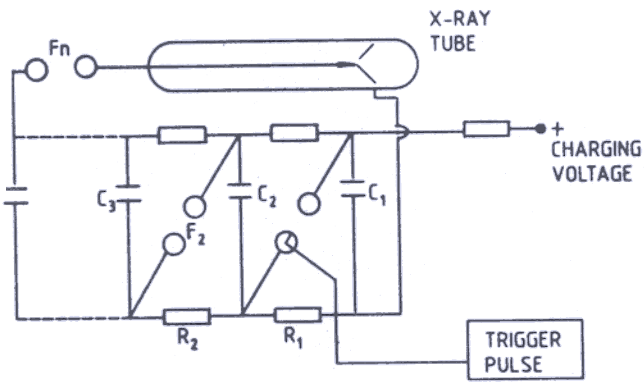

Figure 2. Schematic circuit diagram of a Marx pulse generator.

The 450 kV flash x-ray system configuration is given in Fig. 3. The system was used and the experiments were designed to obtain jet length, jet particle velocities, break-up time, etc for the shaped charges. Trials were conducted for 30, 60 and 90 mm shaped charges and the velocity of jet particles from tip downwards, the particulation time, etc were calculated. The experimental technique used for obtaining the data on

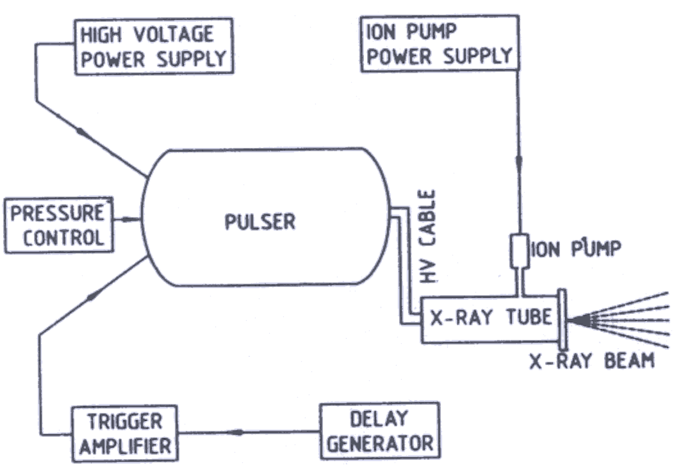

Figure 3. Basic system configuration of 450 kV flash x-ray system.

these shaped charges using 450 kV flash x-ray system, is presented here. The system details are given in Table 1.

Table 1 Specifications of 450 kV flash x-ray system

Parameter	Capability
Output votage	
Output peak current	
Pulse width	
Dose per pulse at 1 m from the tube window	
Focal spot size	
Penetration of steel at 2·5 m SFD (with proper film and intensifying screen)	

2. EXPERIMENTAL

The experimental details and the setting arrangement are shown in Fig. 1. The main purpose of the experiments was to calculate the jet particle velocities from tip downwards and the jet break-up time. The jet has a continuous gradient of the velocity from the tip to slug as a result of which it stretches continuously, and at some time due to the tensile failure it breaks up into different particles. This process is called jet particulation and the time at which the fully stretched jet breaks up is called the break-up time. This is calculated by the ratio of the length of fully stretched jet to the difference in velocity of the jet tip and the velocity of the slowest jet particle which is likely to contribute to the penetration, i.e., 3 mm/μs. Two x-ray tubes used in the system were kept in vertical plane symmetrically with the line of fire at a distance of 1 m away from each other and facing towards the line of fire so that the x-rays were incident at right angle to the line of fire. The angle between the two x-ray tubes with respect to horizontal plane was such that the line of fire passed through the intersection point of the axis of the x-ray tubes as shown in Fig. 1. The distances between the line of fire, the source and the cassettes (film) located parallel to that of line of fire were chosen to ensure safety and to obtain sharp image of the event. During the exposure, care was taken to protect the entire system configuration during the firing. To trigger the system, various modes of triggering devices, such as PCB screens, aluminium probes (foils), and ionisation probe, were tried. Finally, an ionisation probe embedded in explosives with suitable delay was used. Necessary arrangement was also made for collimation to avoid double exposure from two tubes which were to be triggered at different times. The radiograph being a shadowgraph, the image is magnified depending on various distances between the x-ray source, line of fire and the cassettes, which varies from experiment to experiment. To evaluate the magnification factor, the 'fiducial markers' were used at known distances close to the line of fire which gave the shadow on the film. This technique is well established and a number of experiments were carried out. The processed radiographs are shown in Figs. 4-6. The actual sizes of the radiographs are 430 × 350 mm and 2000 × 150 mm, but for convenience they have been photographically reduced to 130 × 70 mm and 130 × 100 mm, respectively.

3. RESULTS AND DISCUSSION

The various parameters, such as jet particle velocities, jet break-up time, scaled break-up time and expected penetration, were calculated from the radiographs. Calibration marks were used for the calculation of scale factor. Two radiographs were obtained for a jet by giving different delay to the two x-ray tubes and then the velocities were calculated by measuring the distance travelled by individual particles in the two radiographs. The length of each particle was measured and a cumulative length was calculated which gives maximum length of the fully stretched jet. The results along with the expected/desired values required for the maximum penetration are shown in Table 2. The expected penetration has been obtained from the equation[1,9]

$$P = L . \sqrt{\xi_j/\xi_t}$$

where, P is expected penetration, L is total unbroken jet length, ξ_j is density of the jet material, and ξ_t is density of the target. From this equation, the essential factor for the maximum possible penetration by a shaped charge is (i) the total unbroken jet length which can be determined by adding the lengths of individual particles after jet break-up, and (ii) the density of the liner material, i.e., the purity of the material may be one of the factors which affect the density and hence the penetration.

Further, a quality factor for a liner called scaled break-up time has been calculated by dividing the break-up time by the calibre of a charge. For the present copper liners produced under ideal conditions and explosives this factor is as high as 2.5 mm/μs. To calculate these parameters, jet particle velocities of 3 mm/μs and above only are considered, as only these particles contribute towards penetration[9]. It is indicated that the maximum tip velocity achievable at present is 9.5 mm/μs.

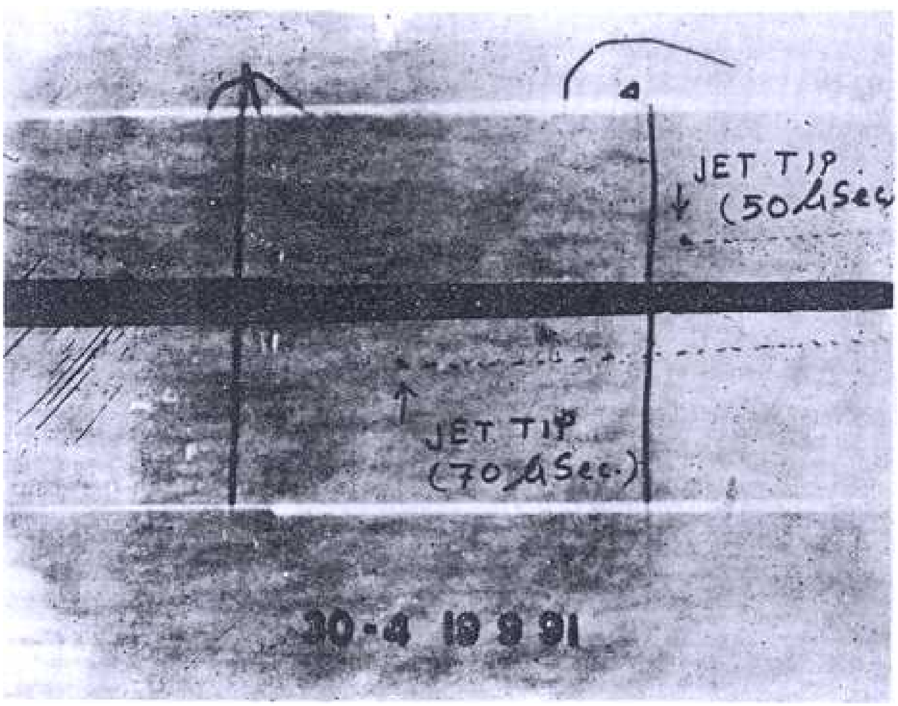

Figure 4. Radiograph of 30 mm charge (a) 50 μs, and (b) 70 μs.

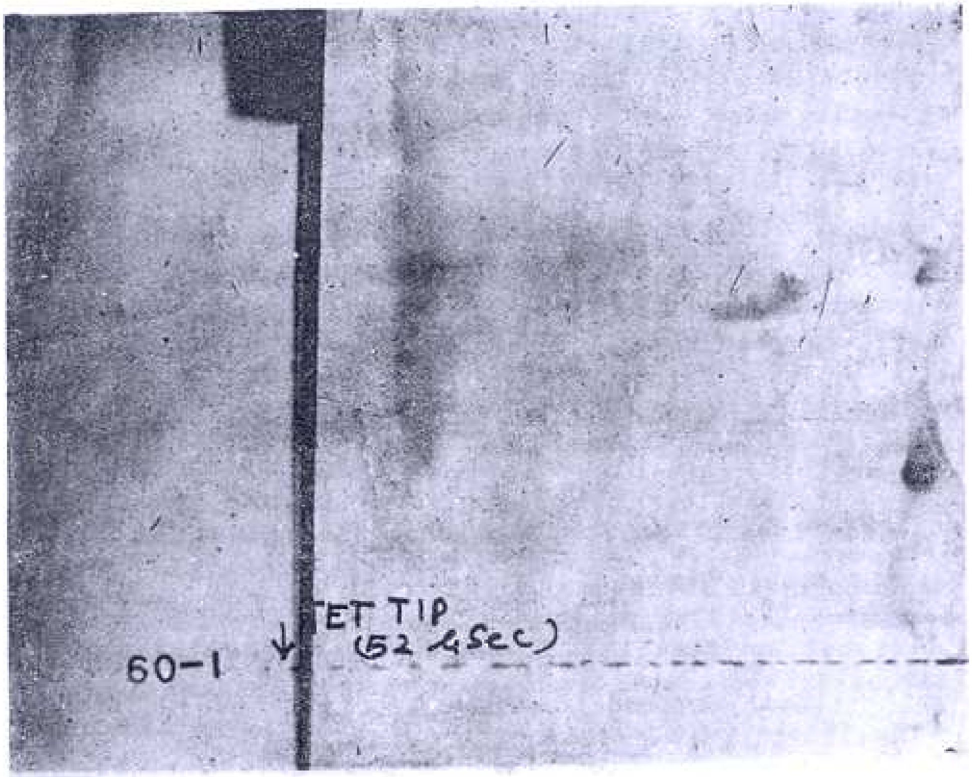

Figure 6. Radiograph of 90 mm charge (a) 160 μs, and (b) 260 μs.

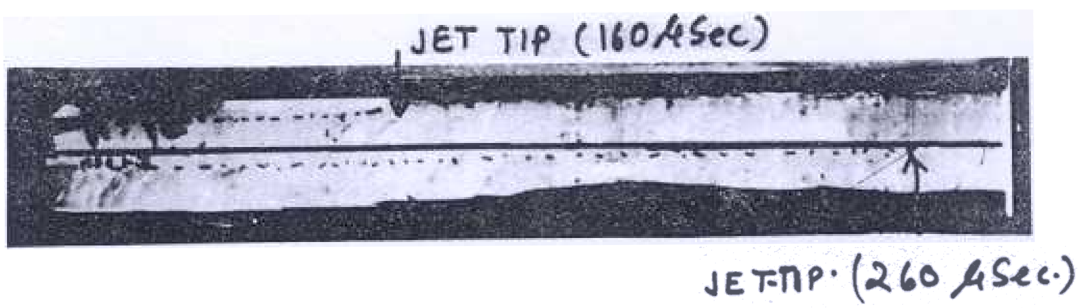

Figure 5. Radiograph of 60 mm charge 52 μs.

Table 2. Computed results for 30, 60 & 90 mm shaped charges

Parameter	Charge calibre (mm)			Reported[9]
	30	60	90	(achievable)
Minimum jet particle velocity considered in calculation (mm/μs)	3.06	3.17	3.19	
Maximum jet particle velocity obtained	5.62	5.475	7.17	9.0
Total jet length (mm)	92.28	157.62	530.0	
Jet break-up time (μs)	36.04	68.38	133.71	
Sealed break-up time (mm/μs)	1.2	1.14	1.49	2.5
Expected maximum penetration in RHA (mm)	98.55	168.33	566.04	

Considering the results, it is concluded that there is ample scope for improvement in the shaped charges used for these trials, and the flash x-ray is one of the powerful techniques which could be used to the maximum extent to evaluate the performance of a shaped charge.

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